

Designing Spacecraft and Mission Operations Plans to Meet Flight Crew Radiation Dose Requirements:

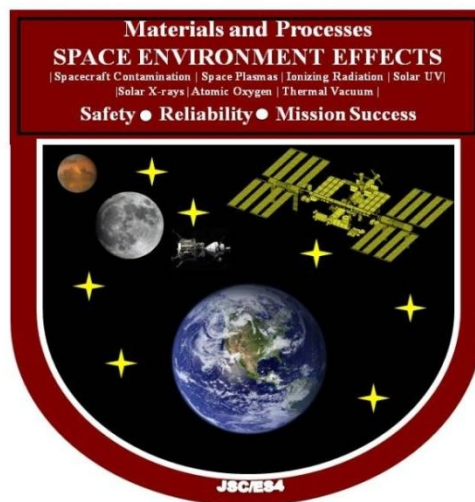
Why is this an “Epic Challenge” for Long-Term Manned Interplanetary Flight

(Hint – It’s About the Money)

NASA/MIT Workshop

06/26/12

NASA/JSC/ES4/Steve Koontz



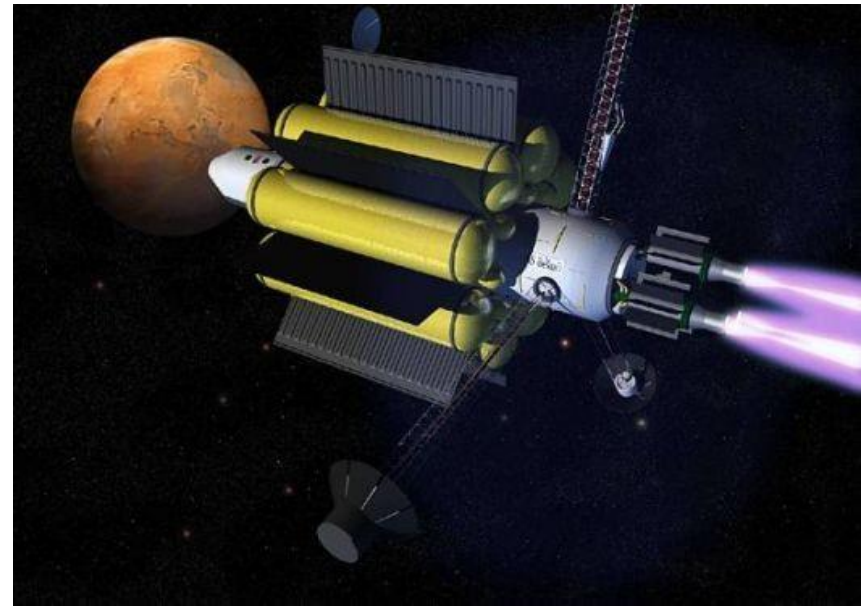
"NASA engineers are working on a clever new idea for shielding astronauts from cosmic rays."

If you put the tanks containing the fuel and water needed for the journey on the outside of the living space, they can also function as shielding.

Just like science fiction writer John W. Campbell first proposed in 1936.

Richard Wilkins, director of NASA's Center for Applied Radiation Research at Prairie View A & M University in Texas has conducted a study into liquid shield approaches.

As he puts it "In most [mission] scenarios, you need liquid hydrogen for fuel and you need water. And these are all considered materials that are particularly good for cosmic ray shielding."



Radiation Shielding Concepts and Performance - Galactic Cosmic Rays (GCR)



Presentation Outline

- ***Radiation Shielding Concepts and Performance – Galactic Cosmic Rays (GCRs)***
 - ◆ *Some general considerations*
 - ◆ *Galactic Cosmic Rays*
- ***GCR Shielding I: What material should I use and how much do I need?***
 - ◆ *GCR shielding materials design and verification*
 - ◆ *Spacecraft materials point dose cosmic ray shielding performance – hydrogen content and atomic number*
 - ◆ *Accelerator point dose materials testing*
 - ◆ *Material ranking and selection guidelines*
 - ◆ *Development directions and return on investment (point dose metric)*
 - ◆ *Secondary particle showers in the human body*
 - ✦ *limited return of investment for low-Z, high-hydrogen content materials*
- ***GCR shielding II: How much will it cost?***
 - ◆ *Spacecraft design and verification for mission radiation dose to the crew*
 - ◆ *Habitat volume, shielding areal density, total weight, and launch cost for two habitat volumes*
 - ◆ *It's All about the Money - Historical NASA budgets and budget limits*
- ***So, what can I do about all this?***
 - ◆ *Program Design Architecture Trade Space*
 - ◆ *The Vehicle Design Trade Space*
 - ◆ *Some Near Term Recommendations*
 - ◆ *The Epic Challenges*
- ***Supporting Materials***

Spacecraft Radiation Shielding: Some General Considerations

- **Cumulative radiation dose to spacecraft crew during prolonged interplanetary flight is dominated by:**
 - ◆ Galactic cosmic rays (GCR), and
 - ◆ the occasional solar energetic particle event (SPE), not
 - ◆ photons (x-rays and γ -rays) or electrons (trapped in planetary radiation belts)
 - ✦ http://www.esa.int/TEC/Space_Environment/SEMEF3T4LZE_0.html
 - ✦ <http://www.bnl.gov/medical/nasa/LTSF.asp>
- **Galactic Cosmic Rays and Solar Particle Events**
 - ◆ **SPE**
 - ✦ Extremely high particle flux and radiation dose rate, however,
 - ✦ “Soft” kinetic energy spectra – 0.1 to $>10^3$ MeV/Nucleon – so shielding materials can be effective at reasonable thickness/mass
 - ✦ Short duration – a few days at most – storm shelter concept – reduces vehicle weight
 - ✦ **So, this isn’t the real problem**
 - ◆ **GCR**
 - ✦ Relatively low particle flux and radiation dose rate, however,
 - ✦ “Extremely hard” kinetic energy spectra - 10 to $>10^6$ MeV/Nucleon - shielding with materials is relatively ineffective at reasonable thicknesses/mass
 - ✦ Continuously present (some solar cycle modulations), so dose accumulates during the entire mission
 - ✦ Considerable uncertainty in evaluating human health risks (nothing like GCR in our natural environment)
 - ✦ **This is the real problem!**

Galactic Cosmic Rays

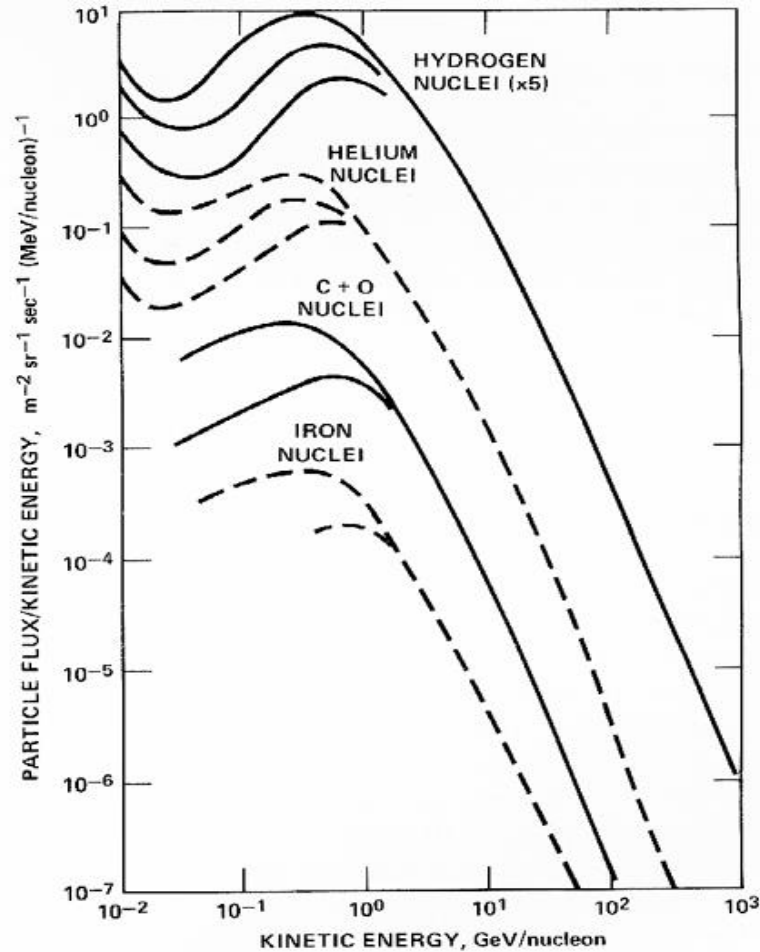
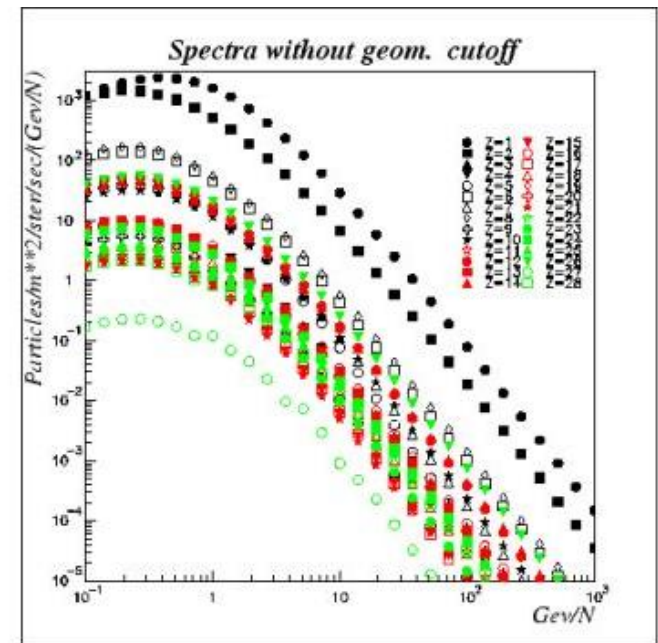
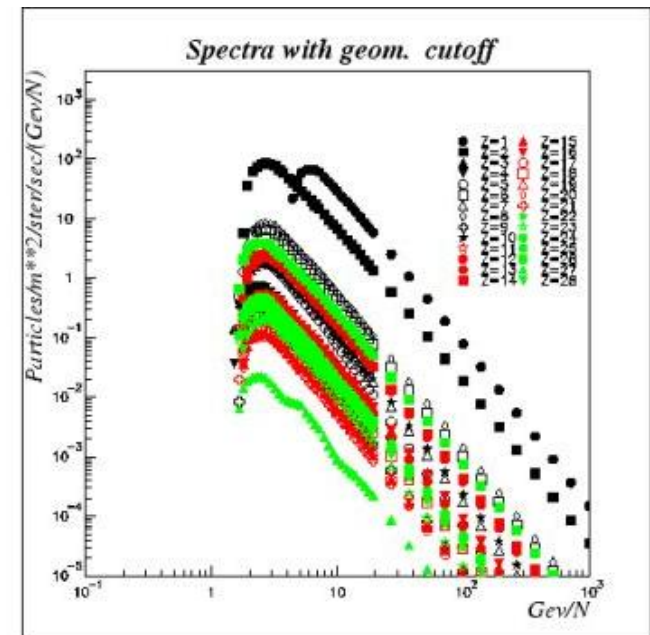


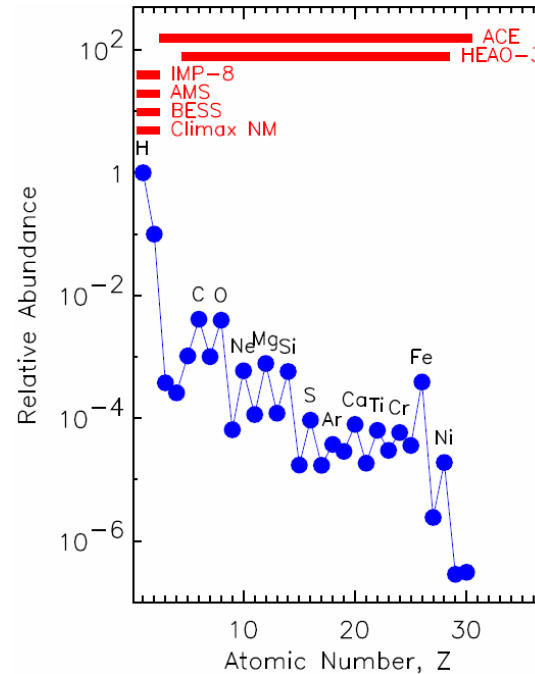
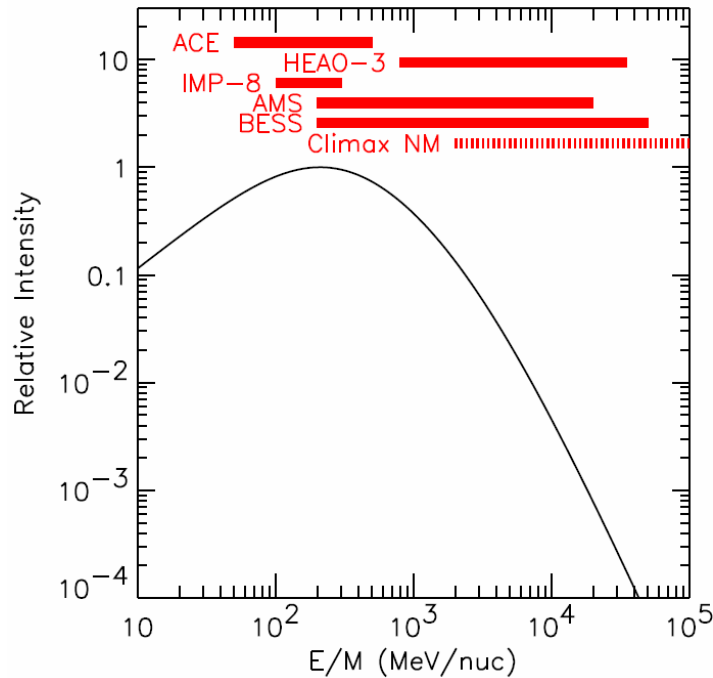
Figure 2-7.— Distribution of energies of galactic cosmic rays. This is a graph of the more abundant nuclear species in cosmic rays as measured near the Earth. Below a few GeV/nucleon these spectra are strongly influenced by the Sun. The different curves for the same species represent measurement extremes resulting from varying solar activity. (Taken from *Physics Today*, Oct. 1974, p. 25.)



Geomagnetic Shielding Effects



Galactic Cosmic Ray Environment “in a nutshell”



<http://pdg.lbl.gov/2010/reviews/rpp2010-rev-cosmic-rays.pdf>

http://www.srl.caltech.edu/personnel/dick/cos_encyc.html

Interplanetary cosmic ray surface flux at 1 AU: NRL/Vanderbilt CREME-96 solar minimum (worst-case) GCR model -

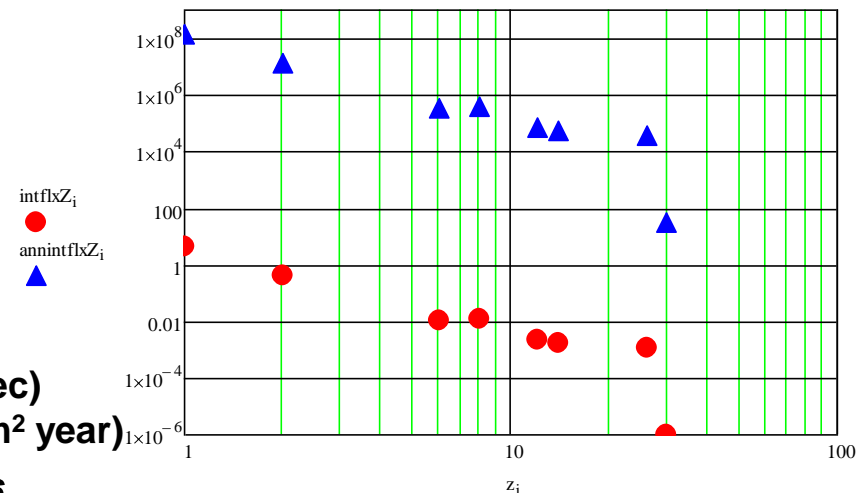
<https://creme-mc.isde.vanderbilt.edu/>

Galactic Cosmic Rays

$\text{annintflxZ}_i =$	$z_i :=$	GCR Nucleus
$1.466 \cdot 10^8$	1	H
$1.383 \cdot 10^7$	2	He
$3.588 \cdot 10^5$	6	C
$3.683 \cdot 10^5$	8	O
$7.232 \cdot 10^4$	12	Mg
$5.177 \cdot 10^4$	14	Si
$3.802 \cdot 10^4$	26	Fe
33.474	30	Zn

● $\text{intflxZ} = \# / (\text{cm}^2 \text{ sec})$

▲ $\text{annintflxZ} = \# / (\text{cm}^2 \text{ year})$



GCR Earth Surface and Atmospheric Environments: Dominated by GCR secondary particle air showers

Earth surface/atmospheric environments

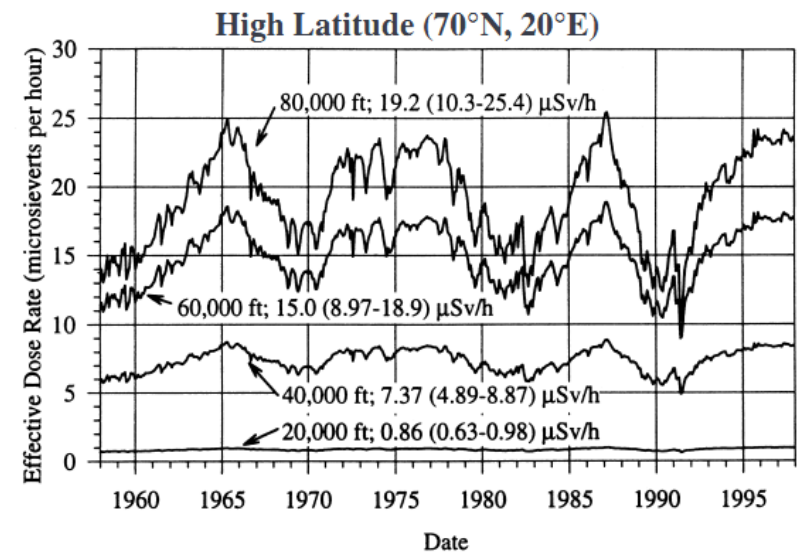
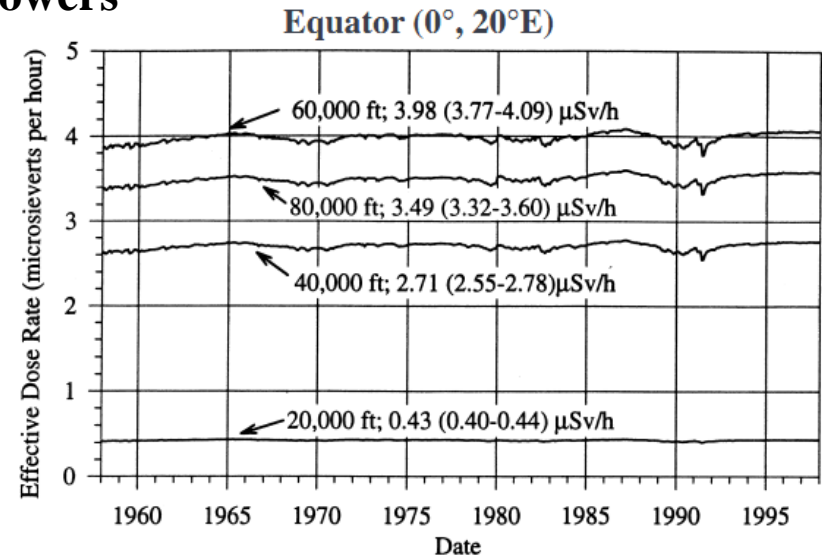
- 1000 grams/cm² air shielding mass at sea level
- latitude dependent geomagnetic shielding
- GCR secondary particle shower products dominate
- GCR contributes about 10% of annual background dose

Commercial and military aviation environments

- Altitude dependent air shielding mass
- Latitude dependent geomagnetic shielding
- Solar cycle modulation of GCR environment
- Latitude dependent solar particle event exposure
- Pfotzer secondary shower particle maximum at about 20 km altitude (mid latitudes)
- Average ISS hourly crew dose rates are on the order of 20 μ Sv/hr - comparable to commercial aircraft dose rates on polar routes at solar minimum



Image Credit -The Boeing Company



Susan Bailey, "Air Crew Radiation Exposure and Overview," *Nuclear News*, pp 32-40, January 2000

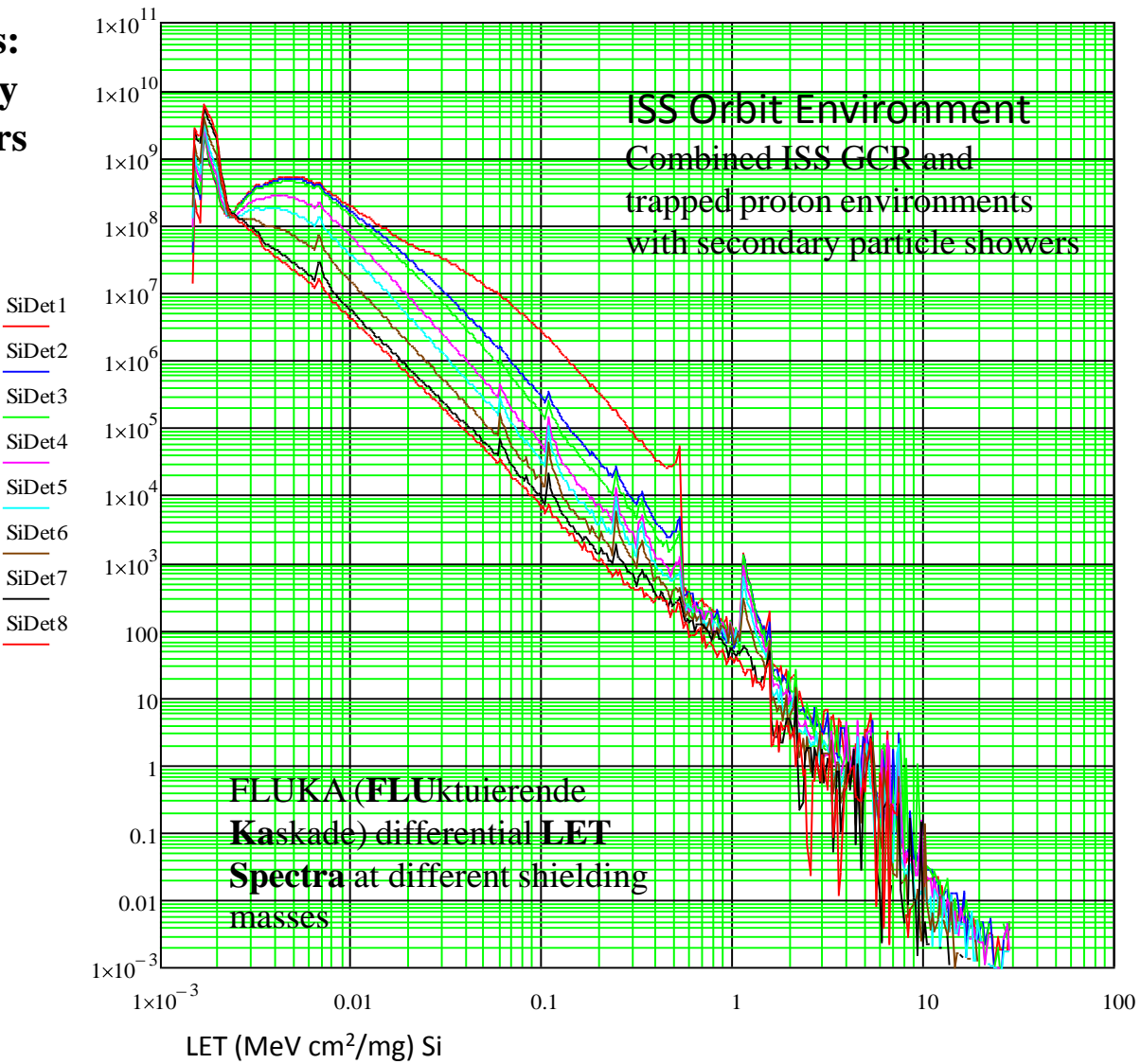
<http://www.ans.org/pubs/magazines/nn/docs/2000-1-3.pdf>

1.2: GCR Exposure Environments: Low Earth Orbit (LEO) – Primary CR and secondary particle showers

The differential LET spectra [#/ (cm² week LET)] at various shielding depths in a concentric spherical shell model spacecraft is shown to the right.

LET spectra are calculated, using the FLUKA (1) Monte Carlo radiation transport code, as the number of particles entering each of the Si detector shells placed at various depths in the concentric spherical shell model (see the table below).

All secondary particle shower processes are enabled and full shielding mass distribution function for each Si shell is utilized in a fully three dimensional calculation. Total ionizing dose and nuclear reactions “star” density is also calculated but not reported here.



Steve Koontz, Brandon Reddell,
Paul Boeder: “Calculating
Spacecraft single Event
Environments with FLUKA, Paper
W-33, Proceedings of the 2011
NSREC Radiation Effects Data
Workshop, IEEE, July 2011

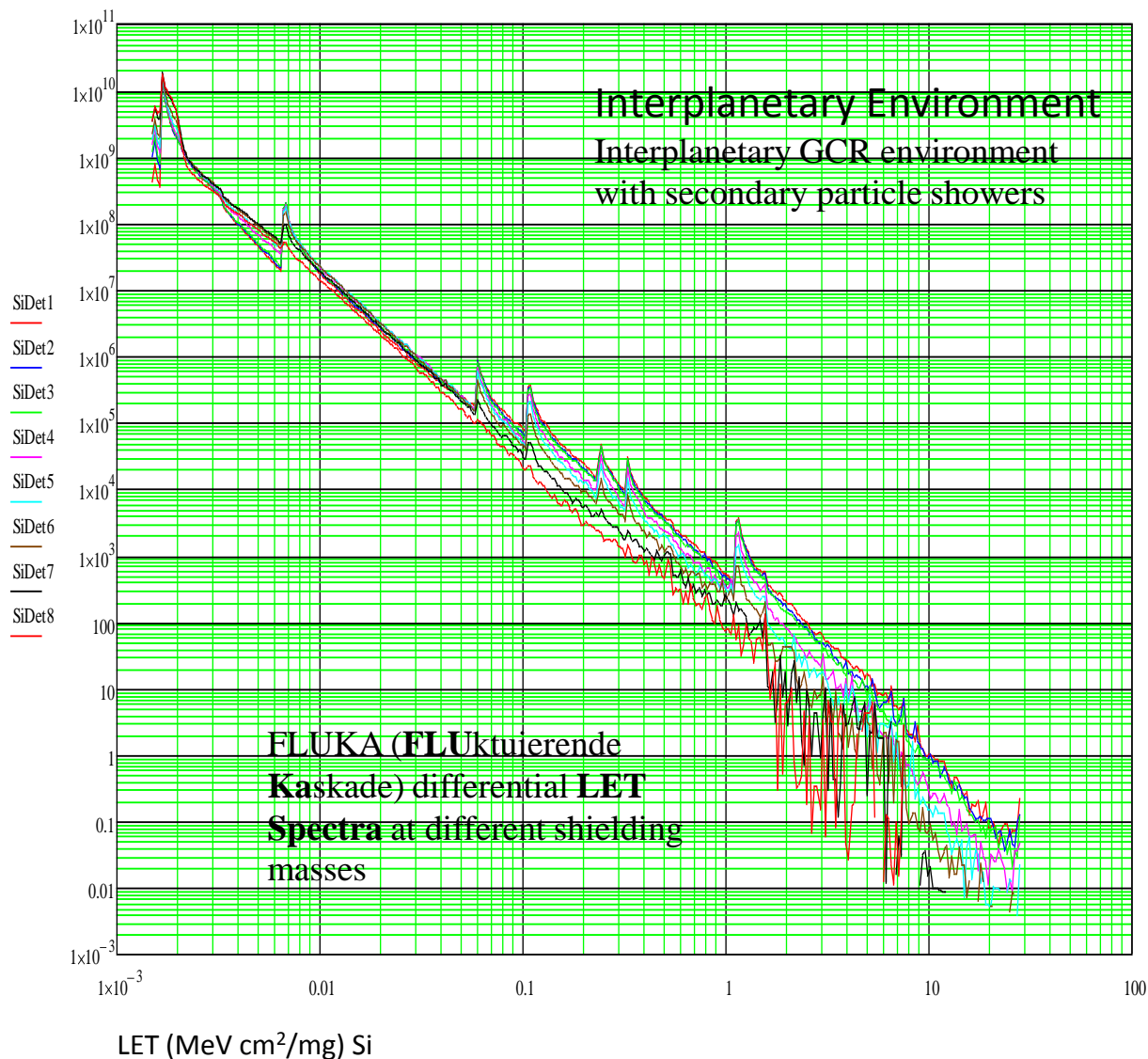
Detector Si Shell	SiDet1	SiDet2	SiDet3	SiDet4	SiDet5	SiDet6	SiDet7	SiDet8
Detector Shell Radius (cm)	5037.4	5037.3	5037.1	5035.6	5033.7	5030.0	5018.9	5000.0
Si Detector Median Al Shielding Mass in g/cm ²	0.15	0.81	1.6	7.9	15.6	31.1	77.5	156.2

1.3 GCR Exposure Environments: Interplanetary Environment – Primary CR and secondary particle showers

The differential LET spectra [$\#/(\text{cm}^2 \text{ week LET})$] at various shielding depths in a concentric spherical shell model spacecraft is shown to the right.

LET spectra are calculated, using the FLUKA (1) Monte Carlo radiation transport code, as the number of particles entering each of the Si detector shells placed at various depths in the concentric spherical shell model (see the table below).

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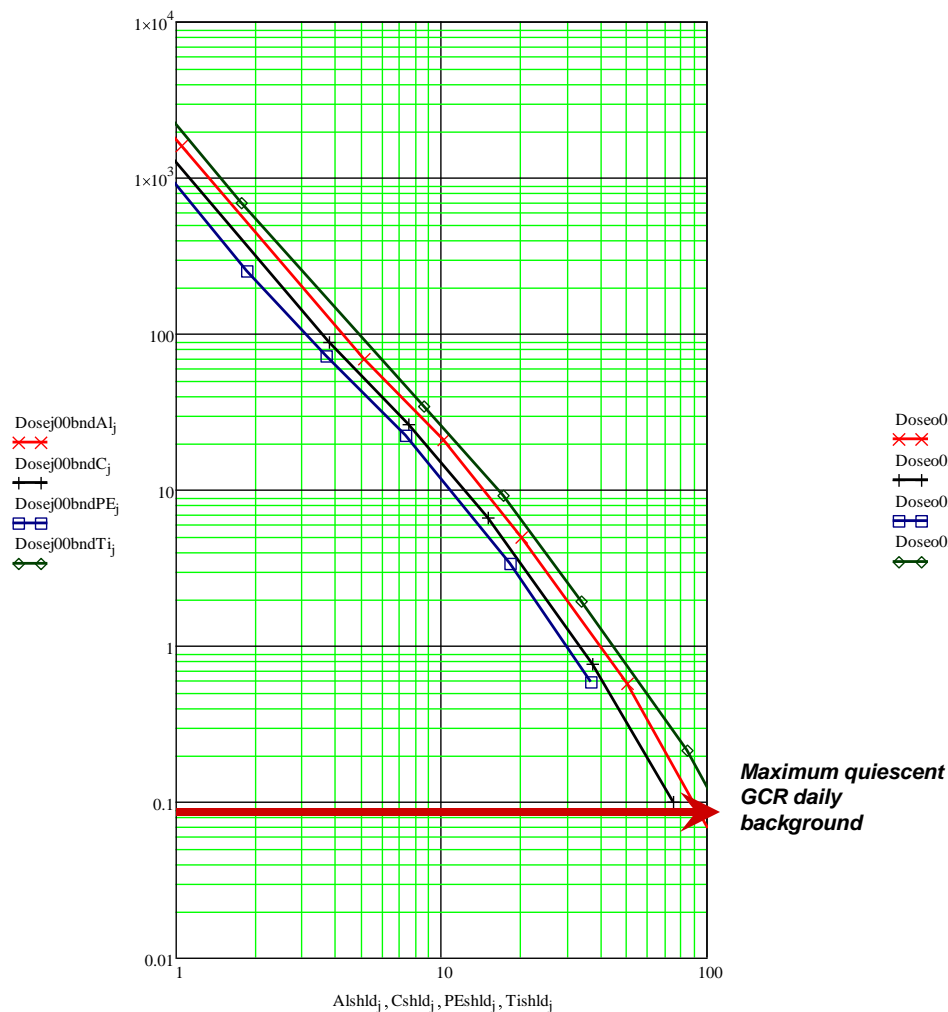


Steve Koontz, Brandon Reddell,
Paul Boeder: “Calculating
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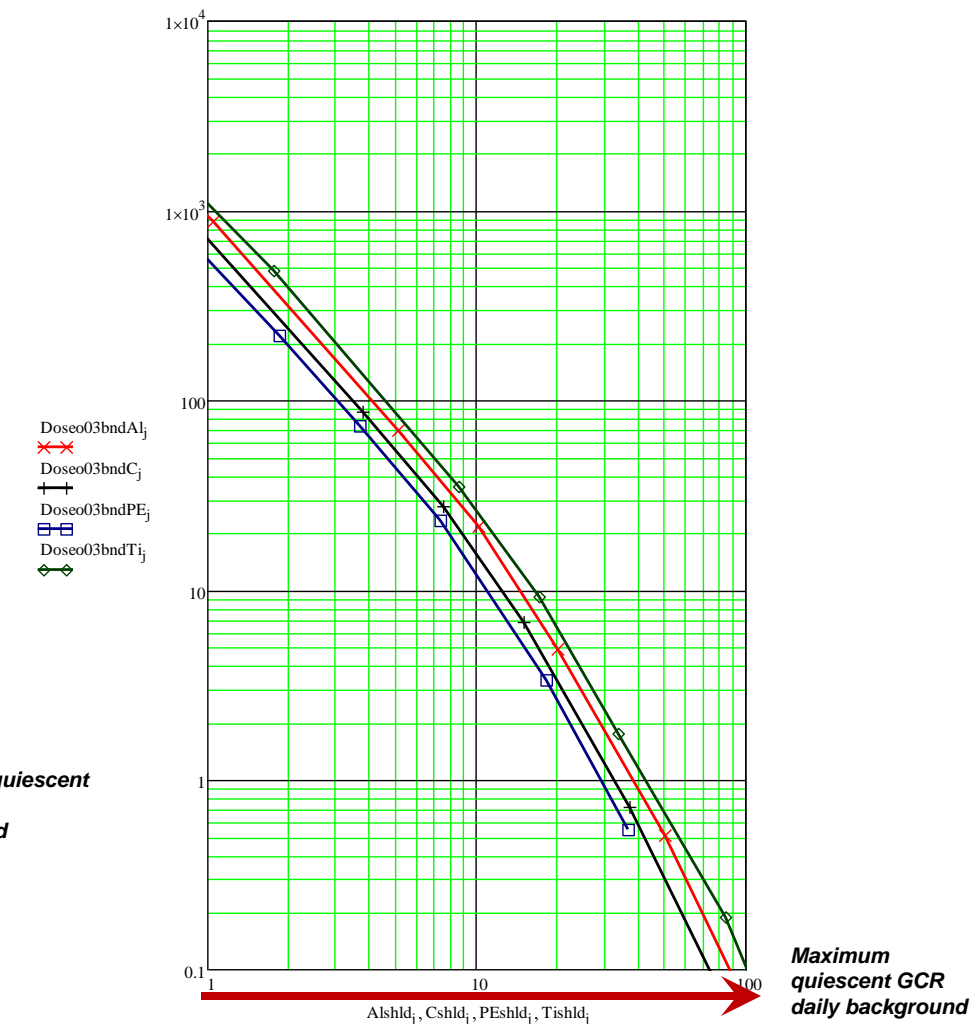
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FLUKA: Solar Particle Events – Dose, Depth, Shielding Material

Steve Koontz, William Atwell, Brandon Reddell, Kristina Rojdev; NASA TP-2010-216133



July 2000 SPE; Dose in cGy



October 2003 SPE; Dose in cGy

***GCR SHIELDING I: WHAT
MATERIAL SHOULD I USE
AND HOW MUCH DO I NEED?***

Spacecraft GCR Shielding Materials

- Point dose calculations and complimentary accelerator testing suggest that low-Z, high- hydrogen content materials may provide acceptable crew shielding against GCR during long duration interplanetary missions with reasonable shielding mass
- Unfortunately point dose calculations and measurements do not take into account the fact that the human body is an extended target capable of producing internal secondary particle showers
 - ◆ See charts 16 and 17
 - ◆ Compare to charts 13, 14, and 15
- Over the range of shielding masses considered to date (10 to 120 g/cm²) the benefits of low-Z, high-hydrogen content materials are small when secondary particle showers inside the human body are taken into account.
 - ◆ Liquid hydrogen is the only substance that continues to show significant benefits
 - ◆ A number of unsolved problems prevent the use liquid hydrogen as a GCR shielding material, e.g. a boiling point of 21 degrees K
- GCR shielding performance depends primarily on atomic number, hydrogen content, and areal density. The state of chemical combination of the elements in a material has little or no effect on GCR shielding performance

Spacecraft Materials Point Dose Cosmic Ray Shielding Performance – Hydrogen Content and Atomic Number

J. W. Wilson, J. Miller, A. Konradi, and F. A. Cucinotta;

Shielding Strategies for Human Space Exploration, NASA Conference Publication 3360 December 1997

<http://srag.jsc.nasa.gov/Publications/TM104782/techmemo.htm>

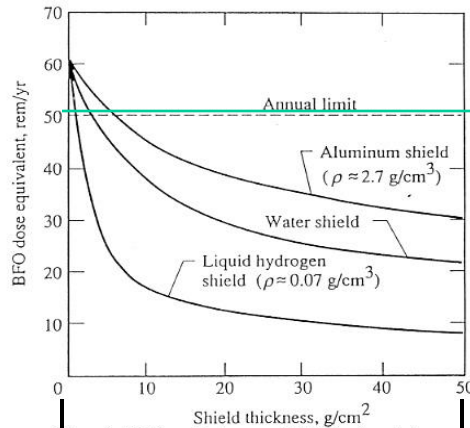
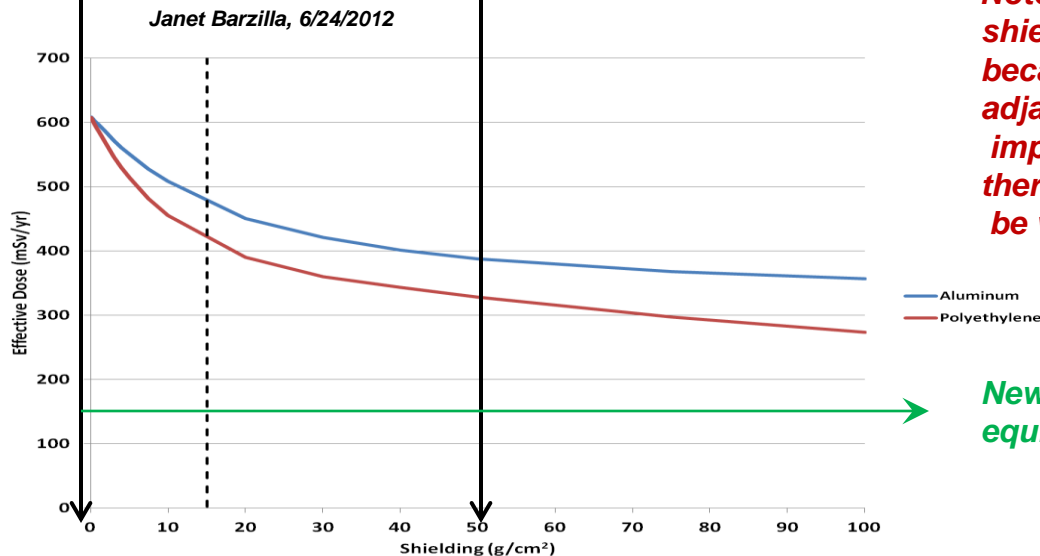


Figure 6. Shielding effectiveness of GCR at solar minimum.

Historical annual limit – 500 mSv/yr to BFO;



Note that liquid hydrogen isn't a simple shielding material. It is a shielding system because maintaining a cryogenic liquid adjacent to a manned crew cabin for several years implies liquid containment and an as yet TBD thermal control system, neither of which will be weightless

New Design Objective - 150 mSv total career equivalent dose

7-142

SHIELDING STRATEGIES FOR HUMAN SPACE EXPLORATION

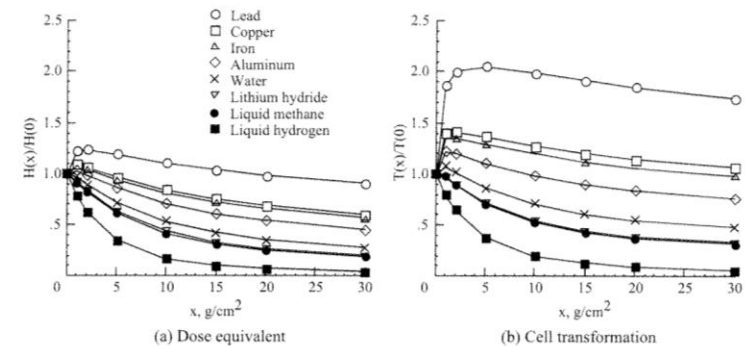
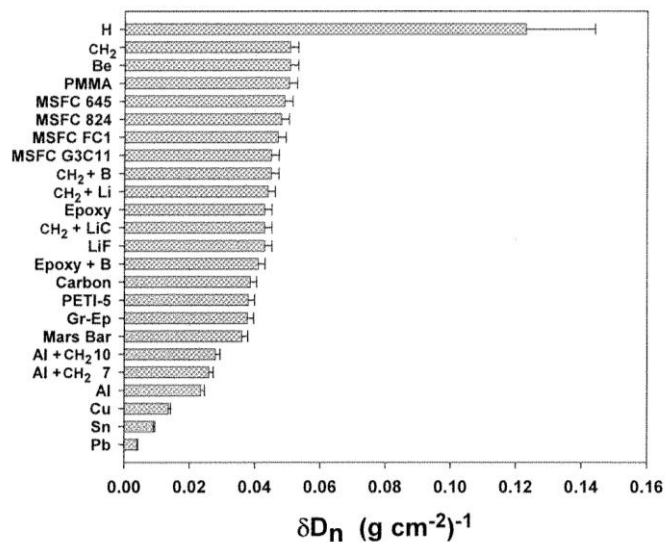
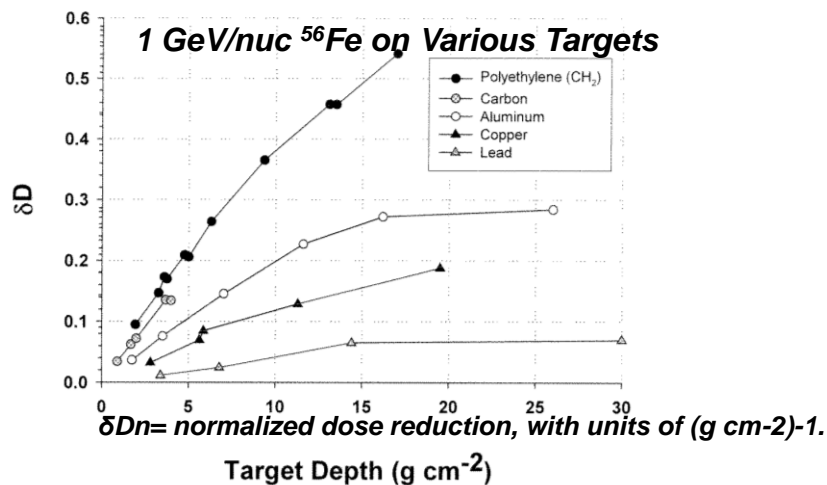
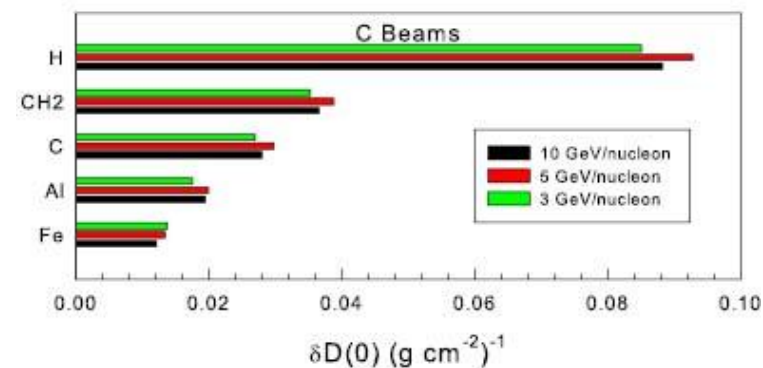
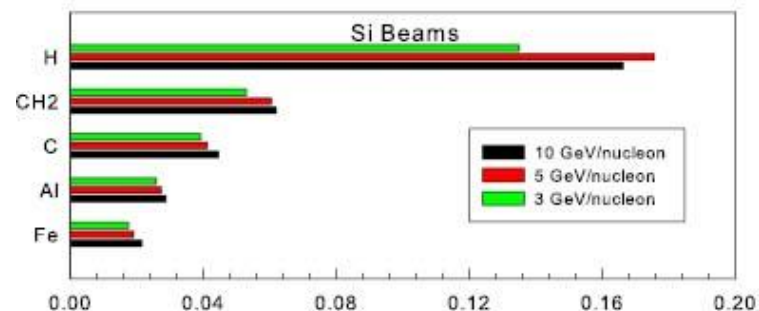
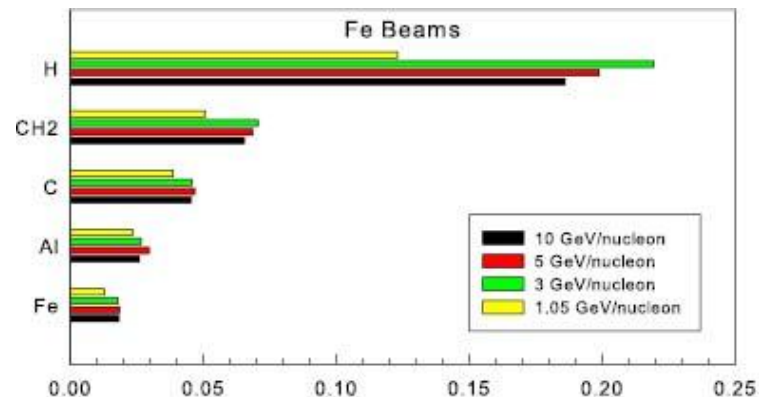


Figure 18. Attenuation of dose equivalent and cell transformation in one year exposure behind several shield materials.

Accelerator point dose testing



Zeitlin, Cary, Guetersloh, Stephen B., Heilbronn, Lawrence H. Miller, Jack ; "Measurements of Materials Shielding Properties with 1 GeV/nuc ^{56}Fe ;" <http://escholarship.org/uc/item/6xh1d1pk>



$\delta D(0) = \delta D_n$ at zero target depth

C. Zeitlin, S. Guetersloh, L. Heilbronn, J. Miller, N. Elkhayari, A. Empl, M. LeBourgeois, B. W. Mayes, **L. Pinsky**, M. Christl, and E. Kuznetsov; "Shielding experiments with high-energy heavy ions for spaceflight applications," *New J. Phys.* 10 (2008) 075007 doi:10.1088/1367-2630/10/7/075007

Development Directions and Return on Investment (point dose metric)

- **Replacing structural aluminum with low Z, H-rich composites**
 - ◆ **Strength to weight ratio better than aerospace aluminum (to reduce weight)**
 - ◆ **No toxicity or flammability issues**
 - ◆ **Structural margins and reliability comparable to aerospace aluminum**

☞ **Understand and control defect driven structural failures**

☞ **Avoid the fate of the Boeing 787**

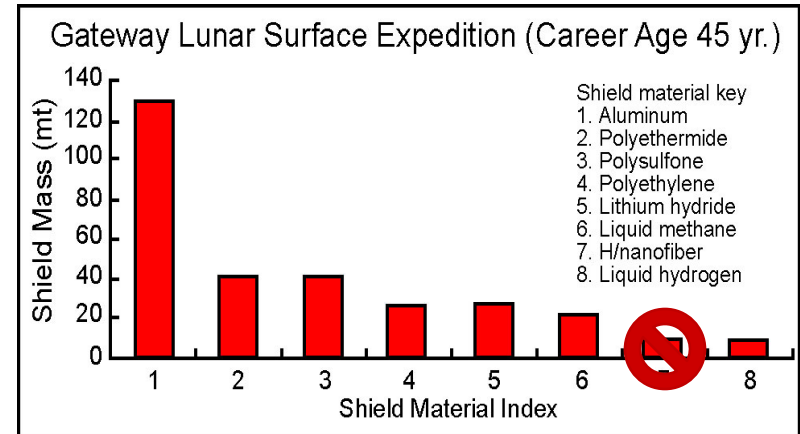
- **Making hydrogen usable as shielding**
 - ◆ **Reliable containment in nano-structured materials**

☞ **Defeat natural limits imposed by chemical bonding and valance**

☞ **Guaranteed hydrogen containment in all space flight environments**

☞ **Radiation damage of containment cannot release hydrogen**

☞ **Guaranteed control of flammability and explosion hazards**



R.K. Tripathi, "Space Exploration: Where we have been, Where we are and Where we are going – a human perspective," 29th International Cosmic Ray Conference Pune (2005) 2, 437-440



The return on investment appears to be enormous, but isn't!

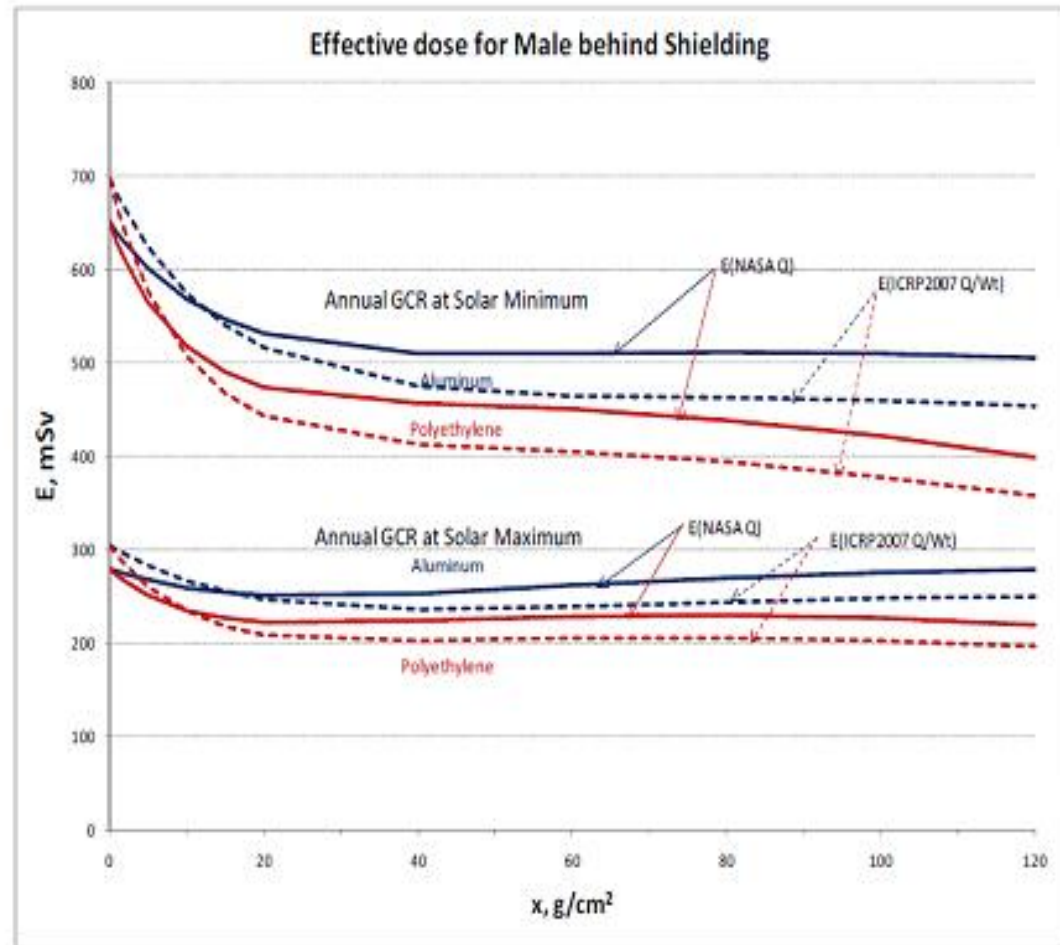
- *However, secondary particle showers inside the human body itself can make important contributions to equivalent dose.*

- *The apparent advantages of low-Z, hydrogen-rich materials much less pronounced than indicated by a point dose comparison.*

- *Note that the shielding performance data on charts 13-15 represent point dose estimates only, not whole body estimates including in-body particle showers.*

- *Compare the graph to the right with those on charts 13-15.*

- *Interesting to note that nothing useful happens between 20 and 120 g/cm² for Al or PE, and $E > 150\text{mSv/y}$*



(Cucinotta, Space Radiation Cancer Risk Projections and uncertainties 2010)

ficients (NCRP, 2000). Fig. 4 shows calculations of the point dose equivalent and the effective dose (tissue averaged organ dose equivalent) for various shielding materials calculated by the HZETRN/BRYNTRN codes for the solar minimum GCR environment and the August of 1972 SPE. Calculations predict that the effects of SPE are readily mitigated by shielding, the effects of GCR are not, and tissue shielding reduces the differences expected when comparing materials. For hydrogen shielding, the GCR effective dose is larger than the point dose because target fragments in tissue contribute about 50% of the effective dose, even though very little secondary radiation is produced directly in the hydrogen shield. Clearly, calculations or measurements of point dose equivalents mis-represent the effectiveness of shielding because of the role of secondary radiation produced in tissue. For calculations, we use 5, 10, and 20 g/cm² as representative of minimal or average shields.

Cucinotta, F., Kim, M. Y., Ren, L.; "Evaluating shielding effectiveness for reducing space radiation cancer risks," Radiation Measurements 41 (2006) 1173 – 1185

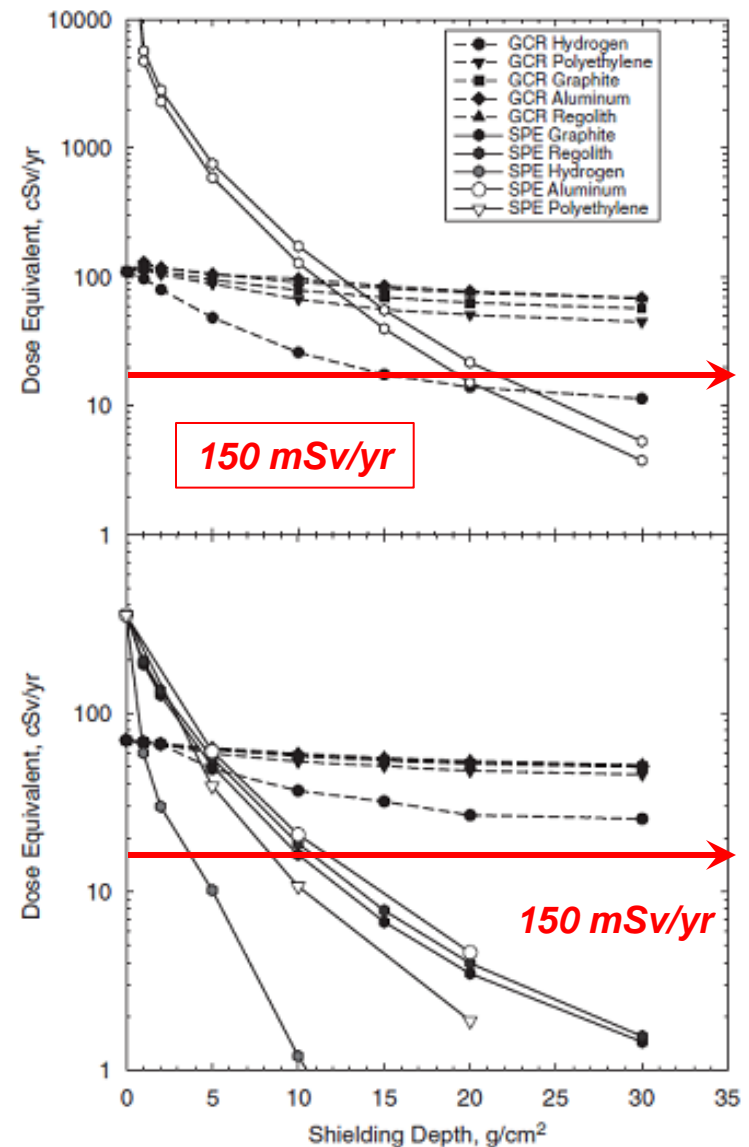


Fig. 4 Point dose equivalent (upper panel) and effective dose (bottom panel) behind various shields for solar minimum GCR and August 1972 SPE (the units for the SPE doses are for total event and not necessarily per year).

GCR SHIELDING II: HOW MUCH WILL IT COST?

Spacecraft design and verification for mission radiation dose to crew:

- **Program specific crew dose design objectives or not-to-exceed limits defined as whole body Equivalent dose some other calculable and measurable dose metric**
 - ◆ **Current Baseline E = 150mSv/yr ; and E= 150mSv Career**
- **GCR and SPE Environments definition and models for design and verification**
 - ◆ Example: The JSC Badhwar/O'Neill GCR environment model including solar cycle modulation
 - ◆ Example: The Moscow State University GCR environment model (as currently implemented in the CREME 96 radiation effects on microelectronics code <https://creme.isde.vanderbilt.edu/>)
 - ◆ A worst-case solar particle event environment . For example, see Steve Koontz, William Atwell, Brandon Reddell, Kristina Rojdev; NASA TP-2010-216133
- **Numerical descriptions of the spacecraft structure and materials – essentially a CAD model of some type that describes the three dimensional structure and composition of the spacecraft**
- **A nuclear reaction and transport code that can calculate the equivalent dose at various locations in the spacecraft by:**
 - ◆ Effectively applying the GCR or SEP design environment to the exterior of the spacecraft as an isotropic particle flux
 - ◆ Simulating particle reaction and transport through the spacecraft materials and
 - ◆ Calculating the required crew dose metric at several selected location in the habitable volume
 - ◆ Semi-empirical deterministic codes include CREME-96 and HZETRN – less accurate and complete but short run times even on a PC.
 - ◆ Physics based Monte-Carlo codes such as FLUKA – complete physics and more accurate in principle but very long run times or large cluster computing systems
 - ◆ Monte Carlo codes are often used to support development and verification of semi-empirical deterministic codes

WHAT IS THE WEIGHT OF THE SHIELDING MASS NEEDED TO COMPLETELY ENCLOSE A CYLINDRICAL HABITAT AT DIFFERENT AREAL DENSITIES BETWEEN 10 G/CM^2 AND 1000 G/CM^2 ?

HOW MUCH DOES IT COST TO LAUNCH THAT WEIGHT TO LEO?

THE ESTIMATE INCLUDES BASELINE VEHICLE AND ANY SUPPLEMENTARY SHIELDING MASS

1) A CYLINDER 20 METERS LONG AND 10 METERS IN DIAMETER (785 M^2 ; $1.6 \times 10^3 \text{ M}^3$)

2) A CYLINDER 7 METERS LONG AND 5 METERS IN DIAMETER ($A = 149 \text{ M}^2$; $V = 137 \text{ M}^3$)

For example, consider shielding a Mars transport vehicle habitable volume, say a cylinder 20 meters long and 10 meters in diameter (785 m^2 ; $1.6 \times 10^3 \text{ m}^3$) - this doesn't look financially feasible does it, unless shielding mass is between 10 and 50 g/cm²?

Shielding Areal Density (g/cm ²)	Total Shielding mass (kg)	Shielding launch cost (@ \$50,000/kg to LEO)	Shielding launch cost (@ \$5,000/kg to LEO)
1000	7.9×10^6	$\$3.93 \times 10^{11}$	$\$3.93 \times 10^{10}$
500	3.9×10^6	$\$1.96 \times 10^{11}$	$\$1.96 \times 10^{10}$
100	7.9×10^5	$\$3.93 \times 10^{10}$	$\$3.93 \times 10^9$
50	3.9×10^5	$\$1.96 \times 10^{10}$	$\$1.96 \times 10^9$
10	7.9×10^4	$\$3.93 \times 10^9$	$\$3.93 \times 10^8$

The numbers used in the calculations are only estimates for the purpose of working the sample problem and do not represent any official NASA design or planning data

Note that the total mass of ISS is only about $4.5 \times 10^5 \text{ kg}$, with about 837 m^3 of pressurized living space

*Shielding a small portion of the vehicle total habitable volume, **say a cylinder 7 meters long and 5 meters in diameter** ($A = 149 \text{ m}^2$; $V = 137 \text{ m}^3$), is much less costly, possibly even feasible if **launch costs** and **shielding mass requirements** are low enough*

Shielding Areal Density (g/cm^2)	Total Shielding mass (kg)	Shielding launch cost (@ \$50,000/kg to LEO)	Shielding launch cost (@ \$5,000/kg to LEO)
1000	1.49×10^6	$\$7.5 \times 10^{10}$	$\$7.5 \times 10^9$
500	7.5×10^5	$\$3.7 \times 10^{10}$	$\$3.7 \times 10^9$
100	1.5×10^5	$\$7.5 \times 10^9$	$\$7.5 \times 10^8$
50	7.5×10^4	$\$3.7 \times 10^9$	$\$3.7 \times 10^8$
10	1.5×10^4	$\$7.9 \times 10^8$	$\$7.4 \times 10^7$

Once again - The numbers used in the calculations are only estimates for the purpose of working the sample problem and do not represent any official NASA design or planning data

Physical thickness corresponding to areal densities

Areal density g/cm²	Aluminum Density = 2.7 g/cm³	Polyethylene or Water Density = 1.0 g/cm³	Liquid Hydrogen Density = 0.07 g/cm³ Boiling point = 20.28° K
1000	370 cm	1,000 cm	14, 285 cm
500	185 cm	500 cm	7,142 cm
100	37 cm	100 cm	1, 428 cm
50	19 cm	50 cm	714 cm
10	3.7 cm	10 cm	142 cm

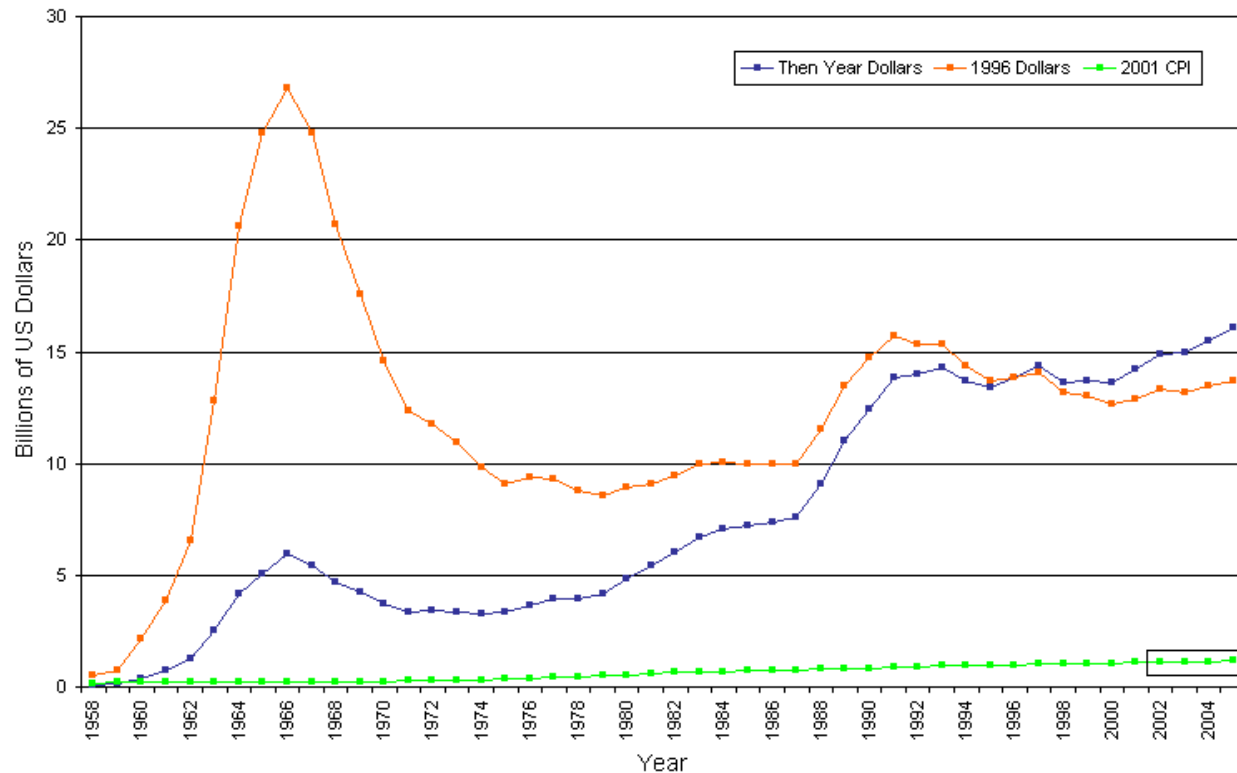
Thickness in cm = (areal density in g/cm²)/(density in g/cm³)

The Bottom Line:

Why space radiation and it's effects are so important to future NASA manned spaceflight programs.

- 1. Financial resource limitations** - NASA's FY 2008 budget of \$17.318 billion represents about 0.6% of the \$2.9 trillion United States federal budget, 35% of total spending on academic scientific research in the United States, and 269% of the National Science Foundation budget, and 61% of the National Institutes of Health budget.
- 2. The budget mark for manned and robotic spaceflight isn't unlimited.** Whatever NASA does has to fit within generally agreed to spending limits

NASA Yearly Budgets



Meeting flight crew dose radiation guidelines and limits:

An important cost and schedule driver for long-term manned interplanetary flight programs

- At present, the most recent estimate of an acceptable spacecraft crew ionizing radiation dose limit (<150 mSv career) combined with historical spacecraft materials and shielding mass (Al @ 10 to 50 grams/cm²) lead to an upper limit (180 days) on manned spaceflight operations outside Earth's magnetosphere
- Referring to chart 15 and 16, even 120g/cm² of PE or Al will not meet the requirement for a 1 year exposure.
 - ◆ Launch cost for shielding the 7 meters long and 5 meters in diameter ($A = 149$ m²; $V = 137$ m³) cylindrical habitat is **on the order of $\$7.5 \times 10^8$ and $\$7.5 \times 10^9$** , a considerable fraction of a realistic NASA annual budget in either case
 - ◆ Shielding the same small habitat at 500 g/cm² implies a launch cost **on the order of $\$3.7 \times 10^9$ to $\$3.7 \times 10^{10}$** which can easily exceed any realistic annual NASA budget allocation
- **Meeting crew ionizing dose requirement with shielding mass launched from Earth's surface is not, at present, a viable solution to the crew dose problem.**



SO, WHAT CAN WE DO ABOUT ALL THIS?

The Program Architecture Design Trade Space

- ◆ **What crew radiation dose requirements should be levied on the project or program hardware?**
 - Crew radiation dose requirements are based on excess cancer death rates estimated from expected crew radiation dose
 - How should we define and verify radiation dose requirements for long term duration manned program hardware?
 - Can a hardware building program accommodate a changing or evolving crew dose requirement?
- ◆ **In-Situ Resource Utilization (ISRU)**
 - Can robotic or manned ISRU systems generate shielding mass, water and propellant in situ and reduce overall program costs?
- ◆ **Con-Ops: Mission Duration**
 - Can program architecture and mission design keep total mission time below 180 to 360 days?
 - Requires advanced propulsion, e.g. nuclear electric VASIMR, for Mars and beyond
- ◆ **Launch Costs**
 - Can launch costs be reduced to \$500 to \$1000 per kg to LEO?
- ◆ **Biomedical and Pharmaceutical radiation dose effects mitigation**
 - What role does this play in a hardware building program and how should it be funded?

The Vehicle Design Trade Space

◆ **Materials selection and habitat configuration**

- Minimize use of structural aluminum and high-Z, low-hydrogen content materials
 - limited return on investment expected here on account of secondary particle showers in the human body itself
 - New low-Z, high hydrogen content structural material must meet an array of safety and reliability requirements independent of radiation performance
- Iterative design (material and configuration) for optimization of spacecraft shielding performance for the crew
 - Wherever possible, every gram of spacecraft mass should be performing two functions – the basic function and a shielding mass function
 - Maximize areal density of spacecraft mass around crew quarters

◆ **Crew GCR (and SPE) radiation dose and propulsion system design trades**

- Nuclear electric, vs. solar electric vs. chemical – what is the most cost effective way to power a sprint mission (180-360 days) to Mars at the integrated spacecraft system level?

◆ **Con-Ops: limit crew time outside small, heavily shielded volumes inside habitat**

- Combine crew quarters and SPE shelter functions?
- Crew quarters and overall habitat volume trade space – more shielding volume means more shielding mass cost

Near Term Epic Challenges

- **Spacecraft structural and shielding materials development**
 - ◆ Reducing spacecraft weight is always a good thing and is one motivation for reducing atomic number and increasing hydrogen content
 - ◆ However, the expected crew dose benefits, even at 120 g/cm^2 , are limited
 - ◆ One possible exception is the use of liquid hydrogen or hydrogen adsorbed in nanoporous solids
 - ✦ Increase storage temperature and reduce thermal control burden
 - ◆ Extend shielding effectiveness studies beyond the traditional limit of about 100 g/cm^2
 - ✦ Accelerator and Monte Carlo simulation (e.g. FLUKA) studies at areal densities between 100 and 1000 g/cm^2 – where is the greatest useful dose reduction ?
- **Moving forward on active shielding**
 - ◆ Magnet coil configurations that dramatically reduce structural loading and support structure mass requirements
 - ◆ Reduce power and cooling requirements
 - ◆ Keep the field out of the crew cabin
- **In-Situ Resource Utilization (ISRU) technology development**
 - ◆ We can't afford to launch shielding mass; but perhaps we can we afford to launch smart ISRU machinery to produce the needed shielding, water, and propellant mass in space from asteroidal, lunar, and Martian resources?
 - ✦ Can large program cost reductions be achieved compared to launching shielding mass, water and propellant from Earth?

Long Term Epic Challenges

● Biomedical and Pharmaceutical Research

◆ More certainty in the relationship between space radiation dose and estimated crew health risks

- ✦ Cancer, Heart Disease, Central Nervous System Effects
- ✦ Removing the enormous uncertainty in the existing health effects estimates may lead to higher crew dose limits and longer acceptable mission times with lower shielding requirements
- ✦ Long term program – 10 years to first products at least

◆ Pharmaceutical Mitigation of Space Radiation Health Effects

- ✦ If successful, this approach could dramatically reduce both health risk and shielding mass requirements
- ✦ Long term program – 10 years to first products at least
- ✦ Possible NASA “Spin-off” products of general benefit in reducing health care costs and treating disease.
- ✦ Promising early results reported at the 22nd Annual NASA Space Radiation Investigators Workshop (Sept 18-21, 2011, League City ,Texas) from several groups

● Advanced Propulsion and Power

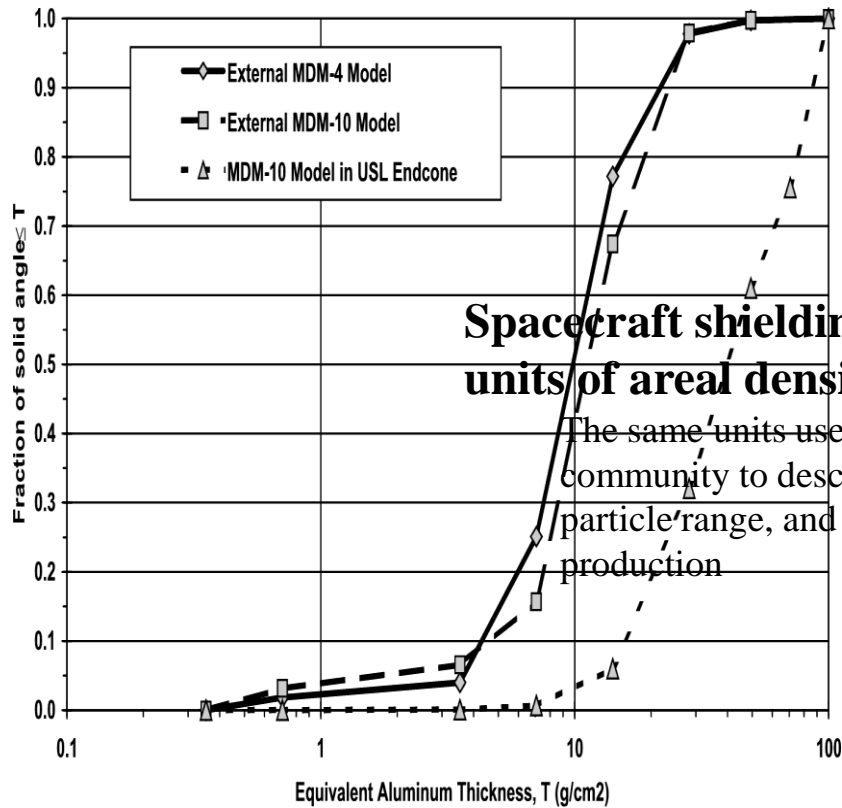
◆ Space Nuclear Power

- ✦ Next generation (Gen-4) fission reactor concepts
- ✦ Flight safety
- ✦ Public safety

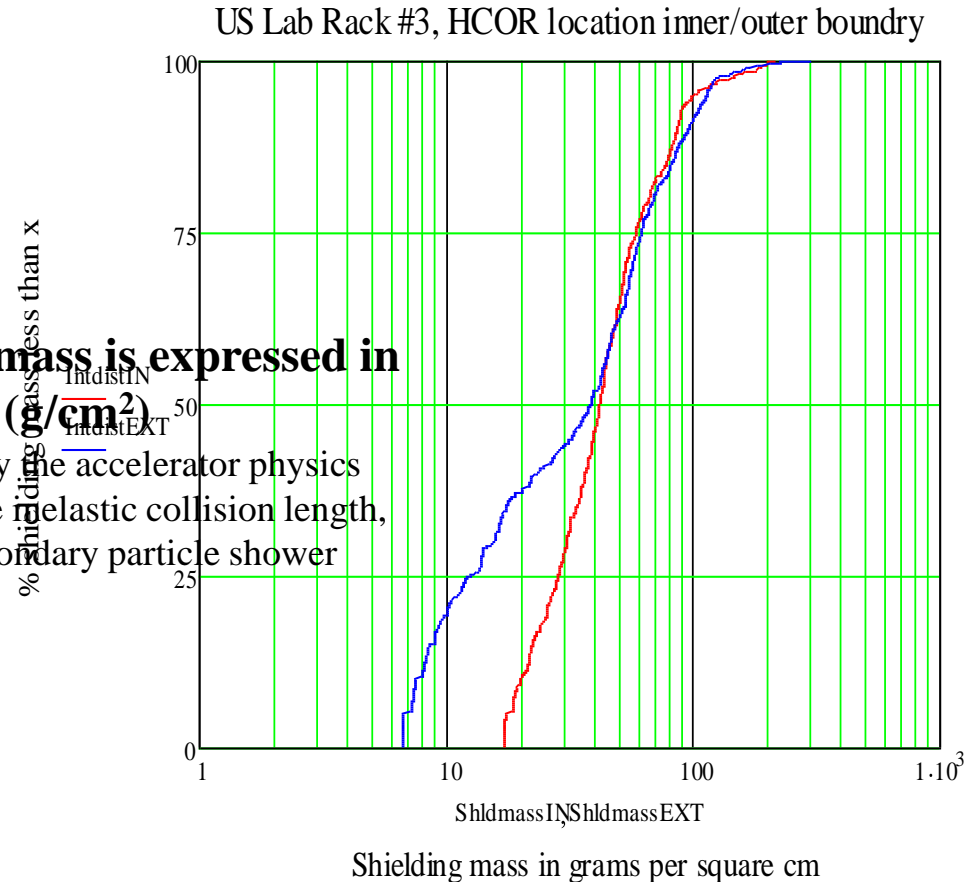
◆ Nuclear Electric Propulsion - VASIMR

SUPPORTING MATERIALS

ISS US Lab and internal/external MDM shielding mass distribution functions (the MDMs are the computers implementing ISS command and data handling functions)



Typical ISS multiplexer- demultiplexer (MDM) shielding mass distribution functions



ISS US Lab HCOR SDRAM Structural Shielding Distributions.

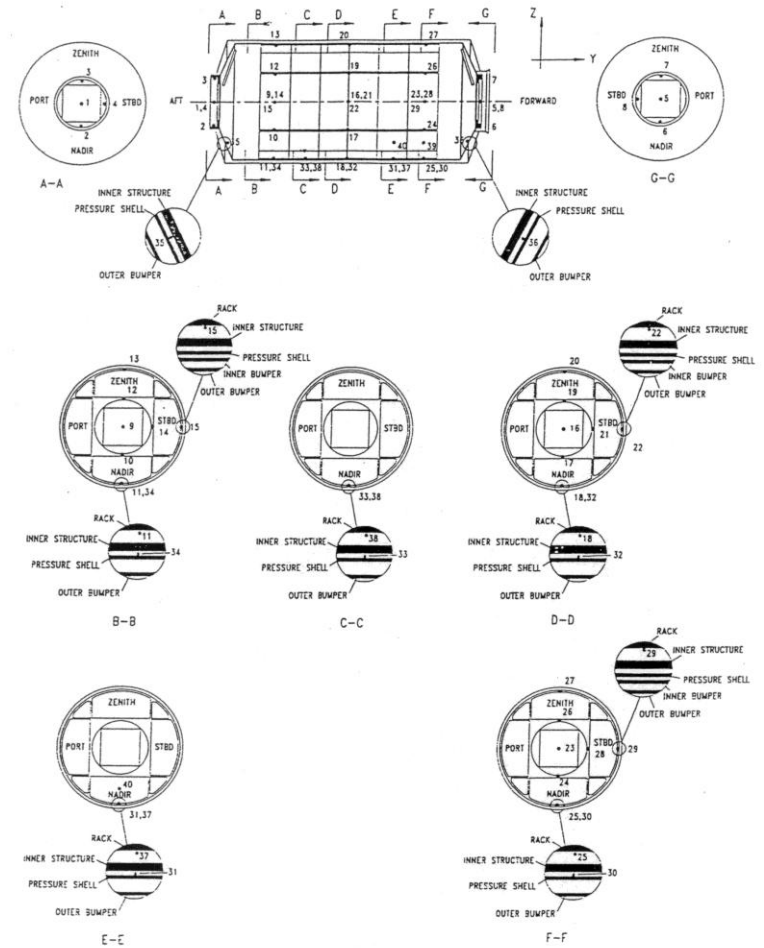
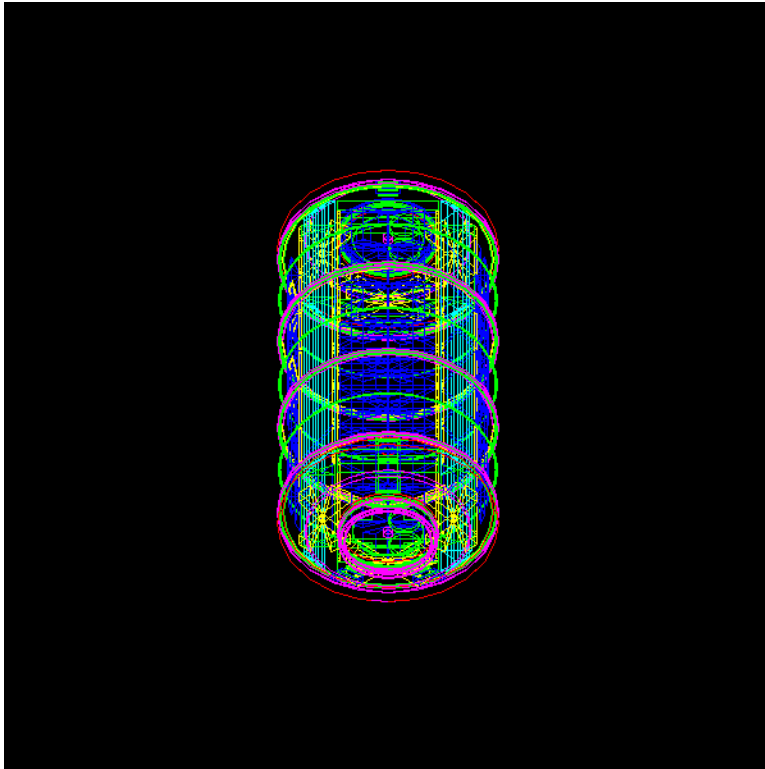
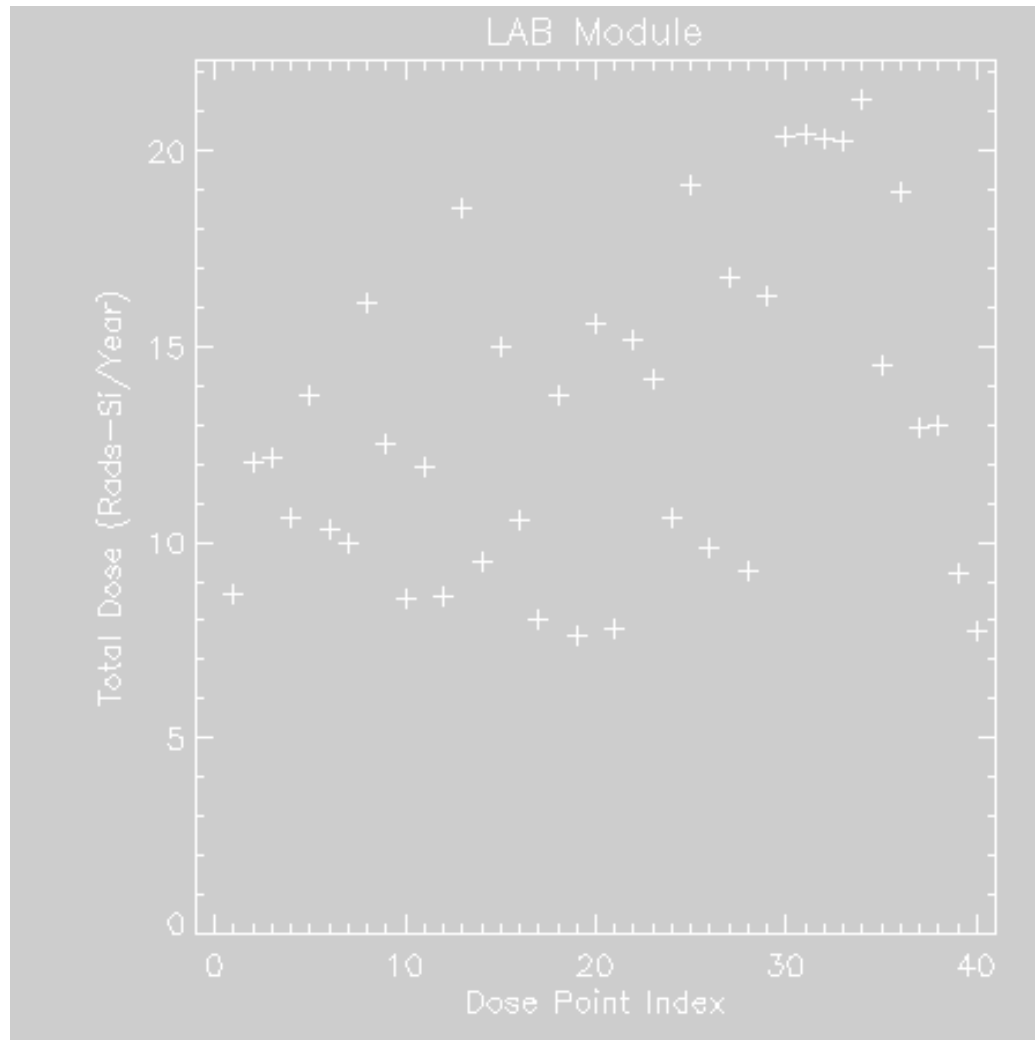


Fig. A-12. Dose points selected in model element LAB (Laboratory Module).



**SSP-30512 DESIGN/VERIFICATION ENVIRONMENT, 500 KM ALTITUDE
COLSA-RTD-ISS-DR-03-008-DOC-B, MSFC, 2003**

GCR-Matter Interactions 1 - Electromagnetic Force

- **High speed charged particles decelerate by losing energy to target substance electrons during coulombic collisions leaving an ionization/damage track**
 - ◆ Nuclear collisions contribute make little contribution to deceleration except at the lowest kinetic energies near end of track.
 - ◆ <http://pdg.lbl.gov/2010/reviews/rpp2010-rev-passage-particles-matter.pdf>
- **dE/dx is the rate of energy transfer: KeV/micron or MeV-cm²/mg**
 - ◆ Linear and nearly constant over most of the particle range - hence the term linear energy transfer (LET)
 - ◆ Nonlinear near end of track – most of the energy is deposited near the end of track in the “Brag Peak”; basis of accelerator hadron therapy for certain cancers
- **Quantified by the relativistic Bethe-Bloch equation (only accounts for electronic stopping)**

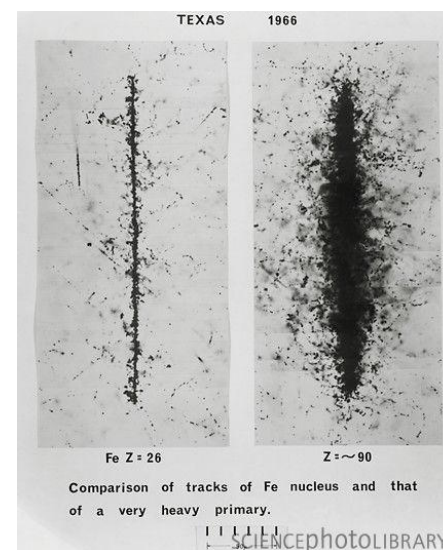
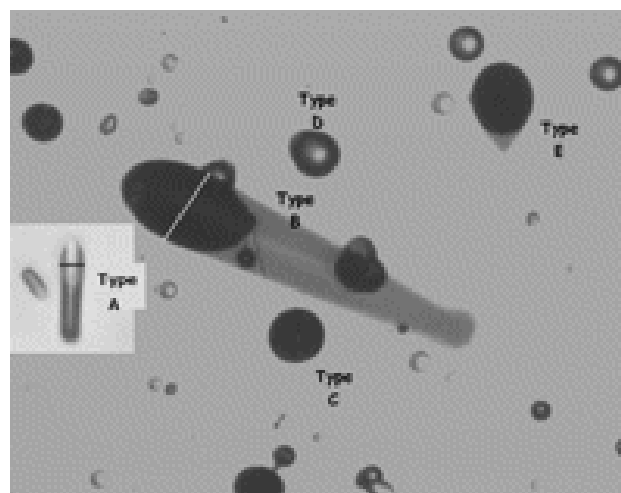
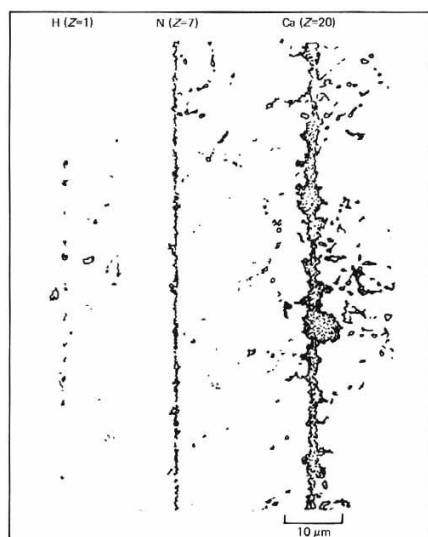
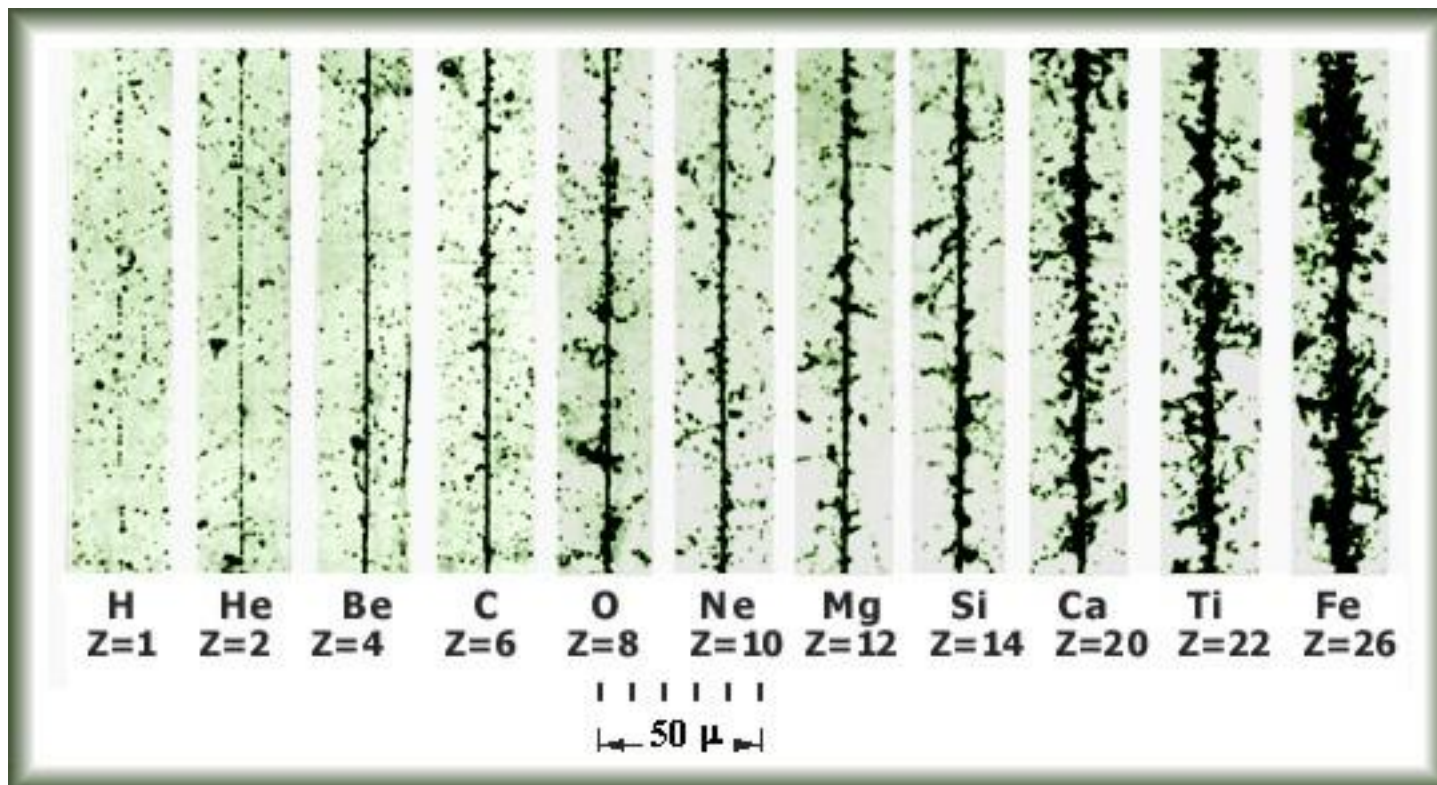
$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0} \right)^2 \cdot \left[\ln \left(\frac{2m_e c^2 \beta^2}{I \cdot (1 - \beta^2)} \right) - \beta^2 \right]$$

- ✦ $\beta = v / c$, v = velocity of the particle, E = energy of the particle, x = distance travelled by the particle, c = speed of light, z = particle charge, e = charge of the electron, m_e = rest mass of the electron, n = electron density of the target, I = mean excitation potential of the target, ϵ_0 = vacuum permittivity
- ✦ $I = 10\text{eV}(Z)$, $n = (N_A Z \rho) / A M_u$; ρ = density of the target, Z = target atomic number, A = target mass number, N_A = Avogadro number, and M_u = Molar mass constant = 1 in SI units

◆ Note that the properties of the target appear only in the n , $\ln(1/I)$, Z/A and ρ terms

- **Widely utilized (free) on-line or downloadable Bethe-Bloch LET and range calculators that will run on your PC**

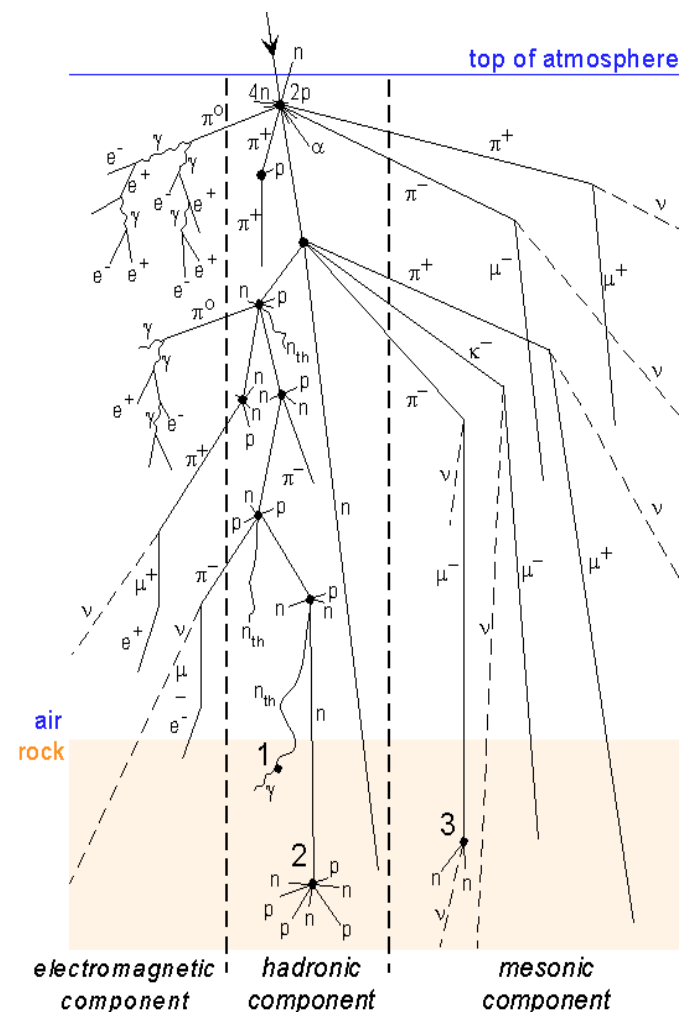
- ✦ <http://www.srim.org/> (includes nuclear stopping at the lowest kinetic energies)
- ✦ <http://tvdg10.phy.bnl.gov/>



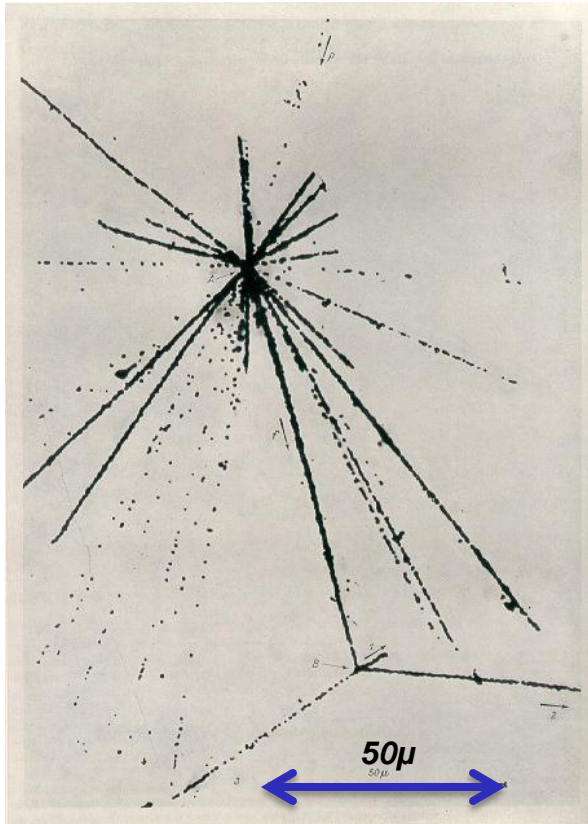
GCR - Matter Interactions II – The Strong or Nuclear Force:

Rules of thumb for relativistic nuclear collisions and secondary particle showers

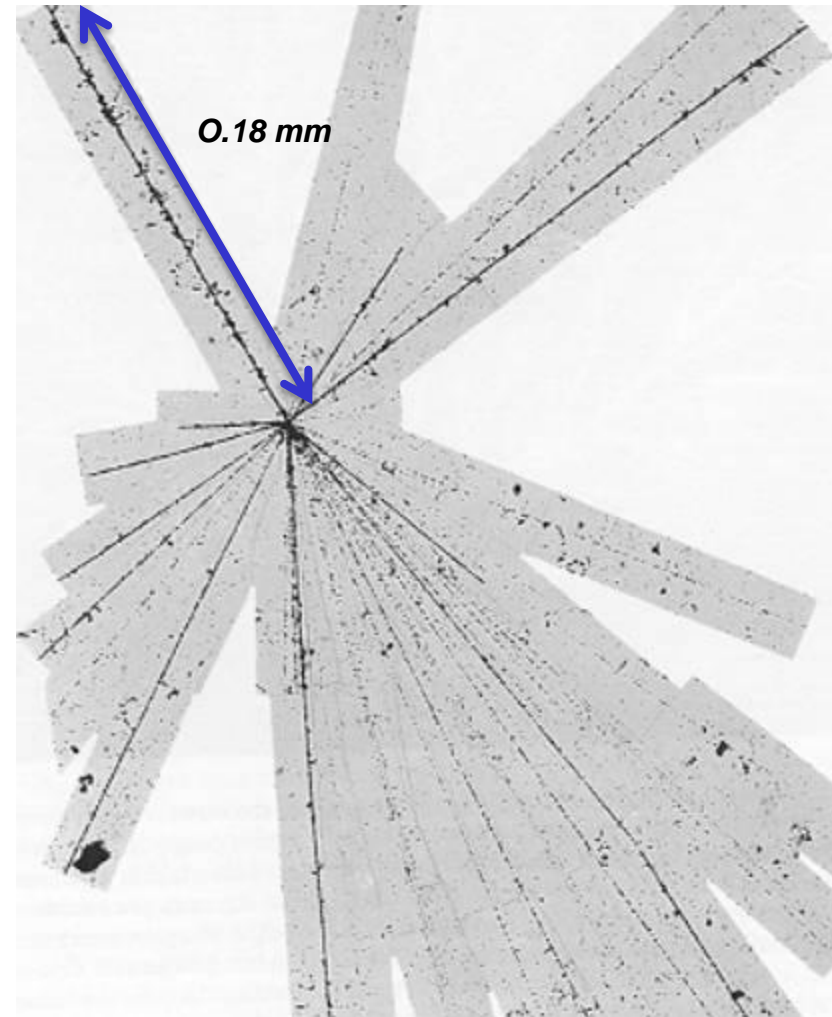
- **Inelastic collisions attenuate the primary flux exponentially and generate secondary particles**
 - ◆ **$N(l) = N(0) \exp(-l/\lambda)$, λ = inelastic collision length (grams/cm²) , l = thickness in g/cm²**
 - ✦ <http://pdg.lbl.gov/2010/reviews/rpp2010-rev-atomic-nuclear-prop.pdf>
 - ❖ λ ranges from **42 g/cm² to 118 g/cm² for protons in various materials**
 - » At fixed target mass, number of collisions decreases with increasing atomic weight (i.e. fewer target nuclei per gram)
 - ❖ λ Scales as **(projectile atomic number)^{0.77}**
 - ❖ λ increases with target atomic number
 - ❖ λ is energy dependent at low (<50 MeV/n) energies
 - ◆ **$\langle n_{\text{event}} \rangle$ = average number of secondary particles per collision event**
 - ◆ **$\langle n_{\text{collision}} \rangle$ is proportional to $A(\text{projectile}) \times A(\text{target}) \times$ (average nuclear thickness function)**
 - ◆ **$\langle n_{\text{shower}} \rangle$ is proportional to primary projectile energy**
- **Secondary particles produced in the first collision expand and propagate the shower via further collisions with target nuclei as described by secondary particle λ s**



GCR nuclear collisions as recorded in nuclear emulsions



Danysz and Pniewski, Philosophical Magazine 44 348 (1953);



Mg nucleus cosmic ray emulsion “star”, i.e. nuclear reaction event

Albert Lim (2000), http://astro.com.sg/articles/Difference_%20btw_Gamma_n_Cosmic_Rays/DiffRays_image001.jpg

